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OCEANIC AND ATMOSPHERIC BOUNDARY LAYER STUDY

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The AIDJEX Modeling Group is developing a predictive model of the dynamics and thermodynamics of the arctic ice cover. To date, an elastic-plastic model of the ice behavior has been developed and operated using field data from AIDJEX pilot programs. A complete model utilizing air stress, water stress, and momentum balance for the ice pack will be developed by the spring of 1975 and checked against the AIDJEX field data taken in a year-long experiment from spring 1975 to spring 1976.

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TECHNICAL REPORT
AIDJEX MODELING GROUP
November 1, 1973 to April 30, 1974

INTRODUCTION

This report describes the technical accomplishments of the AIDJEX Modeling Group from November 1, 1974 through April 1974. The work during this period was supported jointly by the National Science Foundation and the Air Force Office of Scientific Research through ARPA. The AIDJEX Modeling Group is one component of a coordinated theoretical and experimental study of the dynamics and thermodynamics of the arctic ice pack. A paper by N. Untersteiner, Coordinator of AIDJEX, will appear in the *Arctic Bulletin* which reviews the activities through the main experiment to be conducted in 1975-76. A draft copy of this paper is attached. From this coordinated study, there have been two highly successful pilot experiments which were conducted in the spring of 1971 and spring 1972.

Utilizing the field data from the first two pilot programs, the Modeling Group plans to have a predictive dynamic model operating by the time the main AIDJEX field experiment is commenced in the spring of 1975. The AIDJEX Modeling Group is developing a dynamic model to predict the state and motion of pack ice in the Arctic Ocean. The output from this model will include the velocity and stress of the ice field and the state of the ice as represented by the ice thickness distribution (the percentage of any thickness of ice in a given area). From measured barometric pressure data, the model will describe the pertinent physics on a 10-100 kilometer length

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scale with a time resolution of one day. The basic ice model will utilize the momentum equation for the ice (air stress and water stress appear as loadings), an equation of mass balance (ice thickness description) and a constitutive law (stress-strain law) for the pack ice. The Modeling Group will utilize the data from the main field experiment to both drive and check the predictive model utilizing data shortly (within two months) after it has been taken in the field.

The activities of the Modeling Group can be separated into studies of ice mechanics, ice modeling and studies of the atmospheric and oceanic boundary layers. This report will describe the activities in these three areas by the Modeling Group by first summarizing the results for the period in question and then presenting detailed discussion of the various results.

SUMMARY

AIDJEX is a combined theoretical and experimental research program to investigate the relationship of arctic pack ice to its environment. The goal of the AIDJEX Modeling Group is to develop a model (computer program) which will predict the motion and state (stress and thickness) of the arctic pack ice. This model will resolve the behavior of the ice on space scales of 10-100 kilometers and time scales on one day. The model will be developed in such a way as to use barometric pressure maps as the only measure input to the desired predictions. The model will be tested by utilizing other field data taken in the AIDJEX program.

The approach that the Modeling Group has adopted is to study the physical phenomena related to the behavior of the ice at sub-grid scale (space scale much smaller than will be modeled by the predictive model). These sub-grid scale investigations involve, for example, fracture of the ice pack, melting and freezing of the ice, friction and form drag in both the atmospheric and oceanic boundary layer adjacent to the ice, etc. These theoretical investigations of sub-grid scale phenomena will then be checked with field data. The results from these models are used to parameterize the various behaviors in the final AIDJEX ice model.

The AIDJEX ice model now represents the ice as an elastic-plastic material. This implies that the pack ice undergoes no permanent deformation under small loadings derived from the atmospheric or oceanic stresses on the ice. However, as larger stresses are developed, permanent deformations of the ice cover do occur. The elastic-plastic behavior of the pack ice is controlled by a state parameter which is the ice thickness distribution

for a model element. This model has now been documented in a report by Coon et al. in the AIDJEX Bulletin, Reference 2. This report indicates how the sub-grid scale parameterization has utilized the ice mechanics studies related to lead and ridge formation in the arctic pack ice. This model has been used together with AIDJEX field data from the 1972 pilot study to calculate the stress and conditions of arctic ice.

Boundary layer studies associated with the AIDJEX Modeling Group involved determining the air stress and water stress transmitted to the arctic pack ice from the atmosphere and the ocean. Various models have been considered for determining the air stress given the barometric pressure maps for the Arctic Ocean. The Modeling Group has now developed several ways of utilizing the field data which will be obtained to determine the stresses transmitted to the pack ice. Two papers are discussed below which relate to the determination of the ice roughness from profiles of the boundary layer velocities and to a method of calculating the air stress using two similarity constants. These two methods of evaluating data will be used with the main AIDJEX field data when it is obtained.

The AIDJEX Modeling Group is planning to have all software developed by the time data is obtained in the main field experiment in the spring 1975. The software packages will include data processing programs to translate the measured field data in driving forces for the AIDJEX model together with the computer programs needed to model the dynamics and thermodynamics of the ice itself.

ICE MECHANICS

The AIDJEX Modeling Group has adopted the philosophy that the large-scale behavior of pack ice can best be modeled by understanding the detailed mechanisms of ice flow interaction. To this end, studies of mechanisms which fracture the pack ice as well as the mechanisms which form the characteristic rafting and ridging patterns have been made. A paper by R. T. Schwaegler on the fracture of sea ice sheets due to isostatic imbalance appears in AIDJEX Bulletin No. 24, Reference No. 9. This paper shows that the unevenness of the arctic pack ice caused by the mechanical rearranging of ice into ridges and hummock fields leaves the parent ice sheets in a state of isostatic imbalance which can cause fracturing at a later time. This fracturing mechanism can be active at all times of the year and provides a basis for the crack patterns which are observed. This fact is of particular importance to the modelers in that the fractured ice sheets cannot withstand as much tensile stresses as unfractured ones and such information has been incorporated into the stress-strain law for pack ice.

Previous research by the AIDJEX Modeling Group has shown that the largest energy sink in the deformation of pack ice is associated with doing work against the gravitational field in mechanically rearranging the pack ice into rafted and ridged states. The rafting phenomenon has been investigated by R. R. Parmerter and reported in AIDJEX Bulletin No. 23, Reference No. 6. This study determined the stresses which are developed in ice sheets as they override one another. The results clearly indicate that as the ice gets thicker (the order of 50 centimeters), the rafting phenomenon will not occur

and instead the ice sheets will be broken off and ridge formations will begin to occur. These calculations are in agreement with the observed phenomena of thin ice, rafts and thicker ice ridges. Understanding these phenomena are particularly important to the ice modelers because the redistribution of this ice is important as is shown in two papers by D. A. Rothrock and referred to in the next section.

The break-up of floating ice sheets is controlled by the bending phenomena (as indicated by the work of Schwaegler and Parmerter above), and the actual fracture of the ice is associated with crack propagation through the thickness of the ice sheets. A report on the fracture of floating ice sheets has been written by M. M. Mohaghegh. The results of this research were presented at the Sixth Offshore Technology Conference in Dallas, Texas, May 6-8, 1974. Expressions are given for the fracture strength of ice sheets with surface or through-thickness cracks subjected to tensile or shear loadings.

The strength of pack ice on a scale of 10-100 km (which is what the ice modelers are considering) is controlled by cracks which are present. The studies on ice mechanics are used by the ice modelers to parameterize the ice behavior on a large scale.

ICE MODELING

A description of the present AIDJEX ice model with applications is given in Reference No. 2, "Modeling the Pack Ice as an Elastic-Plastic Material, " by M. D. Coon et al., in AIDJEX Bulletin No. 24. This model treats explicitly the growth and melting rates of the pack ice, the formation of leads and pressure ridges, and a mechanical response which, at low stress levels, is elastic and is plastic at some higher stress level (a critical stress or yield stress). The strength of the pack ice is determined by its thickness distribution (the percentage of ice of given thicknesses within a given area), and, therefore, varies because of both thermal and mechanical effects. In this report, the behavior of the model is studied for both idealized deformation and the deformation history of a single element of pack ice as experimentally determined in the 1972 AIDJEX field program.

The flow diagram shown is Figure 5.1, of Reference No. 2. This flow diagram indicates how one calculates the new state of stress and state of the ice given the present stress state, state of the ice, strain rate and thermodynamics (melting and freezing of the ice). The calculation is as follows: Given the strain rate and state of the stress in the ice, it is possible to calculate what the new state of stress would be if the material remains elasti . This new state is then checked to be sure if it is elastic. If so, the new stress state is correct. If not, the state is plastic and the new stress state is determined. Now knowing the stress state, whether the material is elastic or plastic, one can calculate the ice thickness

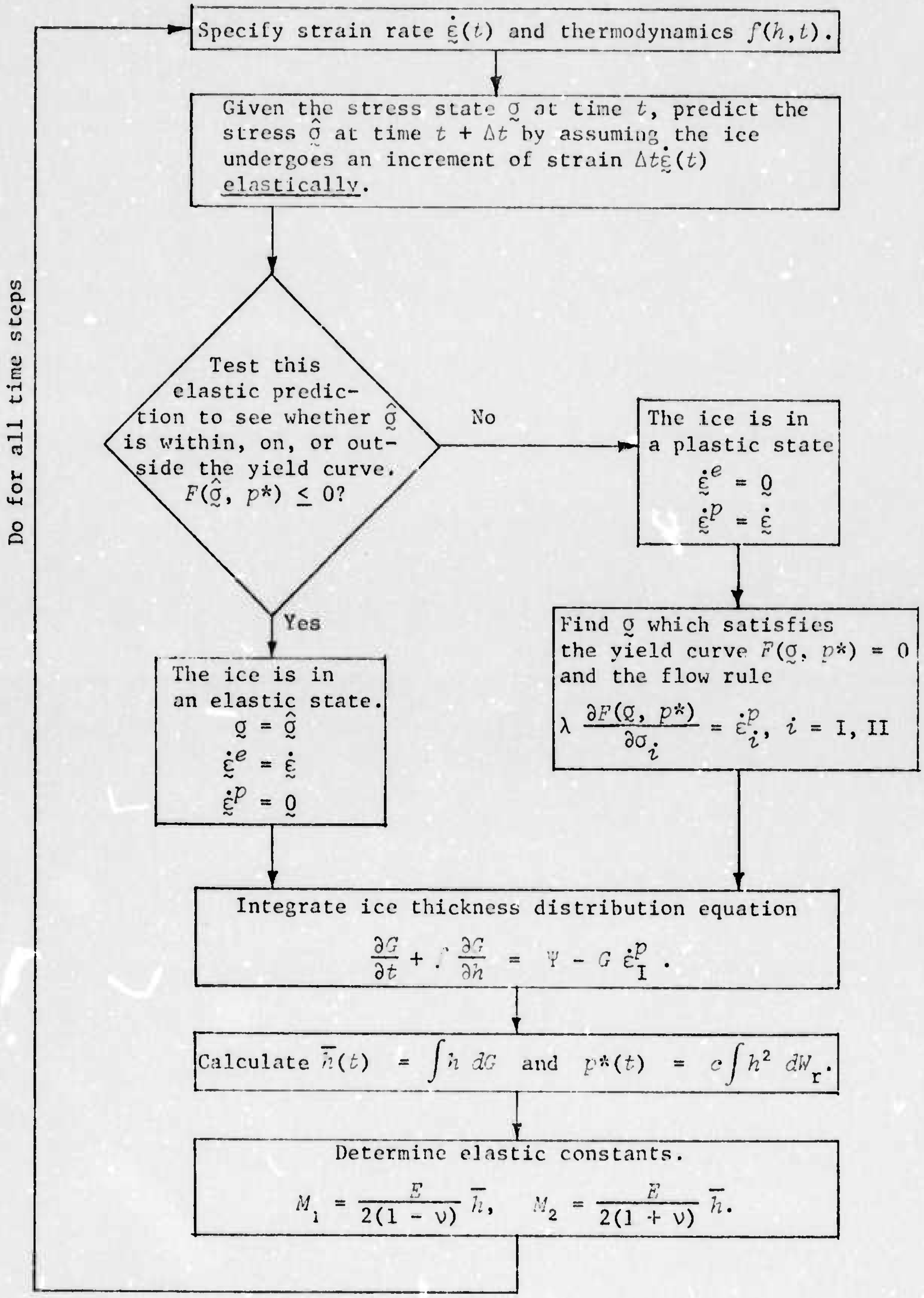

Fig. 5.1. Schematic diagram of construed motion calculation.

distribution from its equation and determine new properties of the ice such as average thickness, $\bar{h}$, critical stress, p^*, and elastic constants, M_1 and M_2. When this is complete, the new state of the stress in the ice as well as its condition--that is, thickness, critical stress and moduli -- is determined and a new cycle is taken.

The report examines various initial conditions and time histories of strain rate to calculate their effect on an element of pack ice. The strain rate history included idealized cases of pure convergence and pure shear as well as strain rate history measured during the 1972 AIDJEX field program. A paper by A. S. Thorndike, Reference No. 10, presents the strains and strain rates calculated from measurements of position of the three drifting sea ice stations (approximately 100 kilometers apart) from the 1972 field program. The measurements were made with the Navy Navigation Satellite System and the paper discusses the techniques used in smoothing the data in time and space to obtain the strains and strain rates. A discussion of errors in the data is included in the report and its conclusion is that strain measured on space scales of 100 kilometers are smooth when viewed in time steps of several hours. This makes comparison of the strain data with calculations for continuum models meaningful.

A paper by M. D. Coon and R. S. Pritchard presented at the Beaufort Sea Symposium, January 1974 in San Francisco, conducted by the Arctic Institute of North America, Reference No. 3, presents a summary of the ice model described in more detail in Reference No. 2. Also, a detailed discussion of more examples utilizing both idealized motions and field deformations is given in this paper.

The present AIDJEX ice model is based on an energy balance which relates energy dissipated in deforming the pack ice to the potential energy stored in ridged sea ice. Papers by D. A. Rothrock, References 7 and 8, indicate how the potential energy in ridging in a one-dimension ridge deformation model can be generalized to a two-dimensional model in which the mechanical portion of the ice thickness redistribution is related to the energy dissipation in the material. The redistribution function can then be related to the plastic yield surface (the stress levels at which permanent deformation occurs). This essentially represents a closure of the systems of equations and allows the plastic yield surface to be related to the mechanical redistribution of the ice. These equations are used in the calculations in the present AIDJEX ice model.

BOUNDARY LAYER STUDIES

The principal driving force of the arctic pack ice is derived from the air stress imparted to the top surface of the ice cover. In the AIDJEX model, this air stress will be derived from a measured barometer pressure field which will be used to calculate geostrophic wind and, in turn, to calculate the air stress. The data from which the barometric pressure maps are generated will be supplemented by velocity and temperature profiles in the boundary layer. This profile data will be used to calculate local forms of surface roughness and air stress. A paper by C. H. Ling and N. Untersteiner, Reference No. 4, reports a method for calculating the roughness parameter of sea ice from velocity profiles. The conventional procedure for determining this roughness parameter is to find an individual roughness for each observed velocity profile. This conventional method leads to a large degree of scatter or the ice roughness parameter. However, a new method of calculating roughness using a number of velocity profiles to find a single value of ice roughness indicates that all data can then be adequately represented by this one roughness. This procedure will be used for handling the data in the main AIDJEX experiment.

There are many procedures for deriving air stress from a barometric pressure map. At this point, the AIDJEX Modeling Group has not settled on the procedure it will use for calculating the air stress associated with the main AIDJEX field data. In fact, different methods will be used to simulate the data in an attempt to find a "best" method and this may, in fact, change with time of the year. A boundary layer model has been presented in a paper by R. A. Brown, Reference No. 1. In this paper, the classical solutions

for the relationship between geostrophic, Ekman layer and surface layer flow have been developed into a continuous solution for semi-infinite flow over a surface. The process used in connecting these various solutions require two parameters. The values of these similarity constants have been determined from data for neutral and stratified boundary layers. These results are presented and as more data is obtained from the main AIDJEX field program, these similarity constants will be better defined.

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THE ARCTIC ICE DYNAMICS JOINT EXPERIMENT

1970 - 1974 - ....

by

N. Untersteiner
University of Washington

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INTRODUCTION

During recent years the terrestrial cryosphere, defined as that part of our physical environment in which snow and ice are the predominant features, has been receiving increased attention in the context of an evolving "new climatology." While it has long been known that climatic conditions on earth must have undergone dramatic variations on a time scale of 10^5 to 10^7 years, small but perceptible changes of the average conditions of the atmosphere and the oceans are being recorded now. The mounting volume of "proxy data" and direct observations, along with our increasing ability to simulate the mechanisms occurring in the terrestrial fluid systems by means of high-speed computer models, has made the advancement of a "theory of climate" one of the most promising areas of research in earth science. The need for such a theory is unquestioned. World population and world resource management are on a collision course. Critical decisions will have to be made in the coming decades affecting the management of arable land, of the oceans, and of fresh water supplies, and these decisions must be based in part on a better understanding of climate and its variations. Increased efforts in climate research have been proposed in several countries.

The study of the cryosphere is an important component of climate research for two reasons. First, because the mean temperature of the earth's surface is close to the freezing point of water, the extent of the cryosphere responds with great sensitivity to climatic change. The massive ice caps of Antarctica and Greenland respond to climatic changes on the order of 10^3 years or longer.

By contrast, the thin, but large, masses of snow on the ground and ice on the sea respond to much more rapid fluctuations in climate (on the order of weeks to years). The second reason for studying the cryosphere is that the presence of snow and ice is a boundary condition for models of the fluid ocean and atmosphere. The discussion in this paper is restricted to one element of the cryosphere--namely sea ice. Our purpose is not to summarize the state of our knowledge about sea ice but to indicate what seem to be the most active and promising areas of sea ice research today.

SEA ICE

The subject of sea ice research can be divided into studies of phenomena that occur on three different spatial scales.

On the smallest scale, one is dealing primarily with the properties of sea ice as a substance (such as salinity, crystal structure, thermal and electrical properties, elastic-plastic properties, etc.). These properties lend themselves to study on small samples and in the laboratory, and hence are relatively well known.

On the medium scale, one is dealing primarily with what might be called "floe-to-floe" interaction (a "floe" in this context might measure from one meter to several kilometers in size). It is on this scale that engineering mechanics finds its most useful application to practical problems. Studies of the bearing capacity of floating plates, buckling, ridging, rafting, and the calculation of the forces exerted by moving ice on rigid structures have recently made significant progress and have become of great practical importance.

The large-scale properties of sea ice are virtually unknown. We believe there is a length scale large enough to include a great number of medium-

scale features such as cracks, leads, ridges, and pieces of ice of different thickness. so that the average behavior of such a large-scale element becomes well defined even though the behavior of the individual medium-scale features is complex and highly variable. The most important variables on this large scale are the extent and thickness of the ice cover and its long-term flow patterns. A model which describes these variables must necessarily treat both the thermodynamic and the mechanical processes by which the ice interacts with the ocean and the atmosphere. The Arctic Ice Dynamics Joint Experiment (AIDJEX), established in 1970, is now engaged in building a model which includes all of the physics which are believed to be important in a full model of the arctic pack ice, but is aimed at solving field equations for only a limited portion of the Arctic Basin. If this limited goal is achieved, and if the proposed coverage by relatively unsophisticated data from a larger area materializes, there is little doubt that it will be possible to develop a realistic model of sea ice.

AIDJEX

A. Summary of Purpose

The specific purpose of AIDJEX is to find a quantitative relationship between large-scale stress and strain fields in sea ice. Given such a relationship, and suitable methods of finding the external stresses resulting from wind and water currents, it will be possible to determine the state of stress in the ice, and the ice velocity fields. The ability to perform such calculations will have the following applications:

1. Since the ice velocity adjusts to the principal driving force, the surface wind, in a matter of a few hours (or less), it will be

possible to interpret a given synoptic atmospheric pressure map diagnostically in terms of ice convergence, divergence, or shear. Such information will be needed when off-shore drilling and surface shipping in ice-covered seas become a reality.

2. It will be possible to predict ice motion (ridging, lead formation, etc.) to the extent that atmospheric pressure fields can be forecast. It is fortunate that the predictive models of the atmosphere now in use forecast pressure better than any other meteorological parameter and show considerable accuracy for periods up to five days.
3. The dynamic ice model being developed by AIDJEX will be an important step toward understanding the long-term (climatic) interaction between atmosphere, cryosphere, and hydrosphere. It will lay the groundwork for a comprehensive analysis of the role of ice-covered seas, which is the primary objective of POLEX.
4. In addition, AIDJEX will continue to yield specific technical and scientific results on
   - energy transfer in a predominantly stable atmospheric boundary layer;
   - heat and momentum exchange in the upper ocean;
   - sea ice morphology;
   - mechanics of pressure ridging; and
   - data buoy technology.

B. Experiment Design

The final scientific plan for AIDJEX that evolved from the intial 1969 version was published in July 1972 as AIDJEX Bulletin No. 15. To this date,

its basic concepts have withstood the onslaught of real data (from the pilot studies) and of budgetary cuts.

The experiment design provides for at least four manned stations about 100 km apart and surrounded by a ring of at least eight automatic drifting buoys. At the manned stations, observations will include:

- position,
- atmospheric pressure,
- wind (air stress),
- relative ocean current (water stress), and
- geostrophic flow in the ocean.

The automatic buoys will report to a central data acquisition system their position, atmospheric pressure, and air temperature.

Figure 1 shows the originally proposed array of buoys (+) and the "most austere experiment" that is now being prepared for deployment in March 1975 and continuous operation until spring 1976.

An important component of the original experiment design was a study of the so-called shear zone, a region close to shore where (especially along the Alaskan and Siberian coasts) a band of open water is frequently found during summer and where, during the cold season, a zone of high shear deformation exists between the shore-fast ice and the more mobile ice further off shore (5-100 km). All previous attempts to model the dynamics of sea ice (including steady-state models) have suffered from our total lack of knowledge of the behavior of the ice in that zone.

In making the transition from the original experiment design to the "most austere experiment," the shear zone experiment had to be eliminated. It was the consensus of all experts involved in the reviewing process that

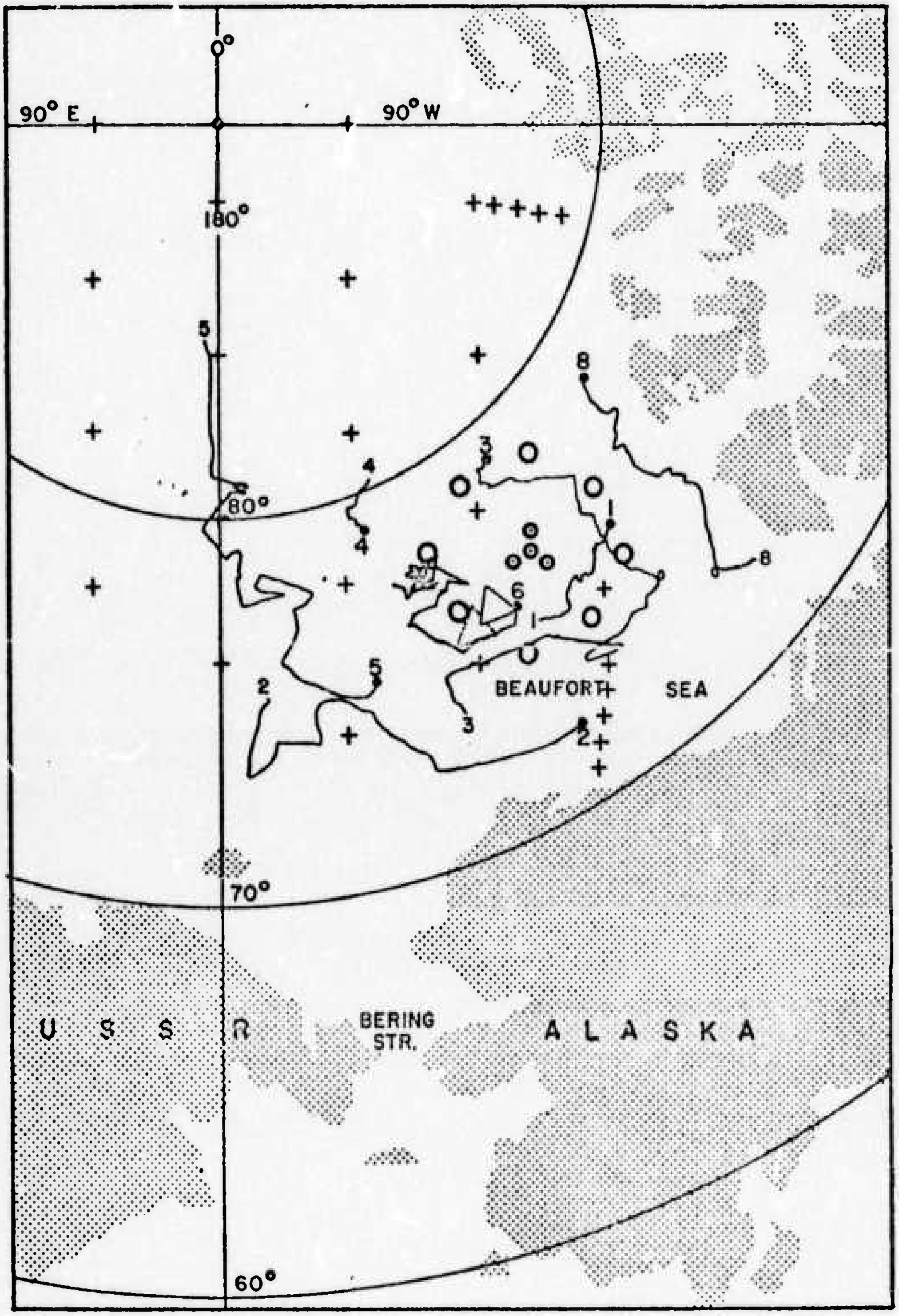


Figure 1

a good interior flow experiment should precede a study of the boundary shear zone. In light of the mounting need for and activity in off-shore prospecting in the Arctic, high priority should be given to the possibility of doing a preliminary shear zone experiment soon.

C. Pilot Studies

The first AIDJEX pilot study took place in March 1970 in the eastern Beaufort Sea and was devoted entirely to oceanographic observations (AIDJEX Bulletin No. 12, February 1972).

The second pilot study was conducted jointly by several U.S. and Canadian principal investigators with logistics support from the Canadian Polar Continental Shelf Project (AIDJEX BulletinsNo. 1, 4, 5, 6, 8, 12, and 13).

The third pilot study (25 February-29 April 1972--see Fig. 1) was the most complex and sophisticated experiment ever conducted on sea ice. It employed an array of manned stations and automatic buoys, including some of the most advanced technology available. Operations, preliminary scientific results, and data are reported in AIDJEX Bulletin Nos.14, 18, 19, 20 and 22.

D. Summary of Results to Date

Automatic data buoys. A detailed description of the 1972 buoys test program is given in AIDJEX Bulletin No. 22 (August 1973). A total of six Interrogation, Recording and Location System (IRLS) buoys, equipped with atmospheric pressure sensors, and temperature sensors at two levels above the ground, were installed in the ice by Twin Otter at an average distance of 400 km from the 1972 main camp (see Fig. 1). The buoys were located by the IRLS system aboard the (continued next page)

Nimbus D satellite which, at the time of the experiment, was a year past its designed life time. The specific configuration of the IRLS buoy for deployment in ice was developed by the Applied Physics Laboratory at the University of Washington under contract with the National Data Buoy Office. The last operating IRLS buoys was, by skillful navigation and some luck, recovered at a location west of Banks Island (72°N, 130°W) on 6 March, 1974 with the support of the Polar Continental Shelf Project, and is now providing useful technical data with respect to battery performance, electronic component aging and deterioration of the buoy structure (Fig. 2).

The principal buoy for the Main Experiment, being developed jointly with the National Data Buoy Office, will have a radio data link with a central facility at one of the manned camps. The motion of the buoys will be measured using the Navy Navigation Satellite System (NavSat) with an expected accuracy of 100 meters.

High accuracy navigation. Satellite navigation systems were operated during the 1972 pilot study at each of the three manned camps. The RMS error was found to be 80 meters. From these data, the components of the two-dimensional strain tensor have been derived to an accuracy of approximately 1 in 1000. As an example, Figure 3 shows the change over time of the area of the station triangle in AIDJEX 1972. The NavSat system for the Main Experiment is being designed to automatically select the best passes from the six navigation satellites presently in orbit. The positioning accuracy of the new NavSat system will be on the order of 10 meters. Its computer will, during the 1975-76 Main Experiment, be part of an integrated data acquisition system which will serve the atmosphere and ocean sensors as well.

Figure 2

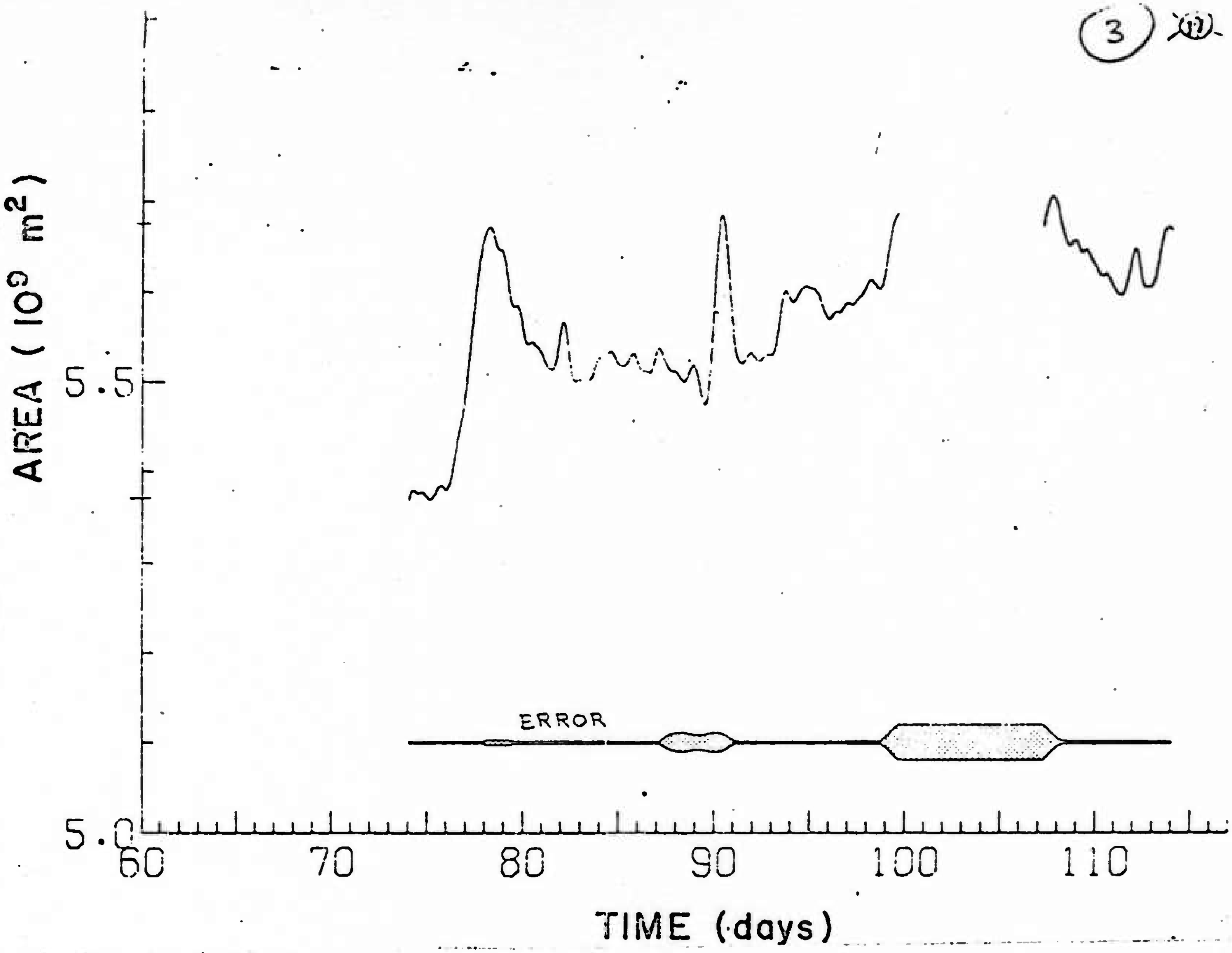


Figure 3

Space and time scales of ice motion. Prior to the 1972 AIDJEX field experiment, two crucial questions were unanswered:

1. What is an appropriate high-frequency cut-off for measurements of ice motion?

2. On what space scale does the pack ice begin to behave as a continuum?

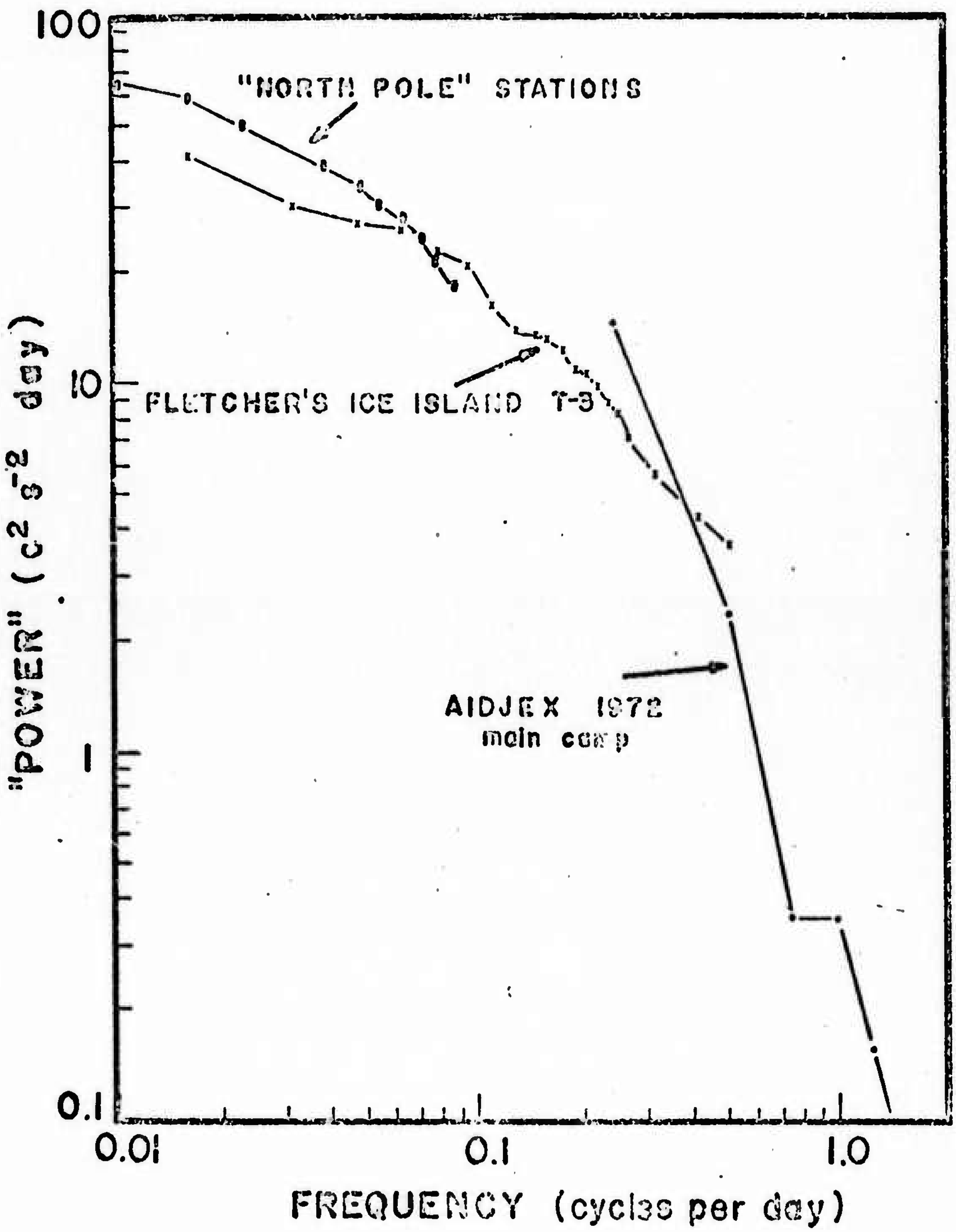
The first question has been answered using data from the satellite navigation system and the acoustic bottom referencing (ABR) system (see AIDJEX Bulletin No. 14). The high sampling rate (10^{-2} sec^{-1}) and the high precision of the ABR (5-10 meters) were adequate to resolve any rapid fluctuations in the ice movement. The data show, however, that for the velocity spectrum, a measure of the amplitude of the velocity fluctuations as a function of their frequencies, drops off dramatically for high frequencies. Ice motions with a period of 12 and 24 hours are clearly documented in the spectral analysis, but their amplitudes are small compared to the low-frequency wind-driven motions.

independently by an extensive set of laser ranging data from a mesoscale strain network (AIDJEX Bulletin No. 21, July 1973), operated by the U.S. Army Cold Regions Research and Engineering Laboratory.

Experimental determination of an adequate space scale, to answer the second question, is nearly impossible because of the immense logistics difficulties in measuring densely in space. Nevertheless, the results obtained on a 100 kilometer scale in 1972 support the theoretical contention in the Scientific Plan that an appropriate scale, if it exists, should lie between 10 and 1000 kilometers. Viewed on this scale, by remote sensing techniques for instance, the pack ice becomes fairly homogeneous or at least smoothly varying. The strain measurements on this scale seem continuous and differentiable, making a continuum hypothesis plausible (Figs. 4a and 4b).

This contention received additional support by a recent analysis of ERTS I images of pack ice in the Beaufort Sea. Figure 5 is one example of several curves obtained for the displacement of a straight line connecting a large number of recognizable features in the pack ice. On the large scale (spacing of manned stations and data buoys during the Main Experiment) the deformation seems to be that of a continuum. The medium-scale perturbations (10^1-10^2 km) represent the mechanical interactions of smaller ensembles of "floes." In its most sophisticated form, the AIDJEX model (Fig. 6) should be capable of representing these medium-scale motions, which may be of particular value in engineering and surface shipping applications. It is envisioned that, through suitable parameterizations, less detailed versions of the model will be developed that will lend themselves to an integration with the global fluid models aimed at understanding climate and climate change.

(4a)


100
10
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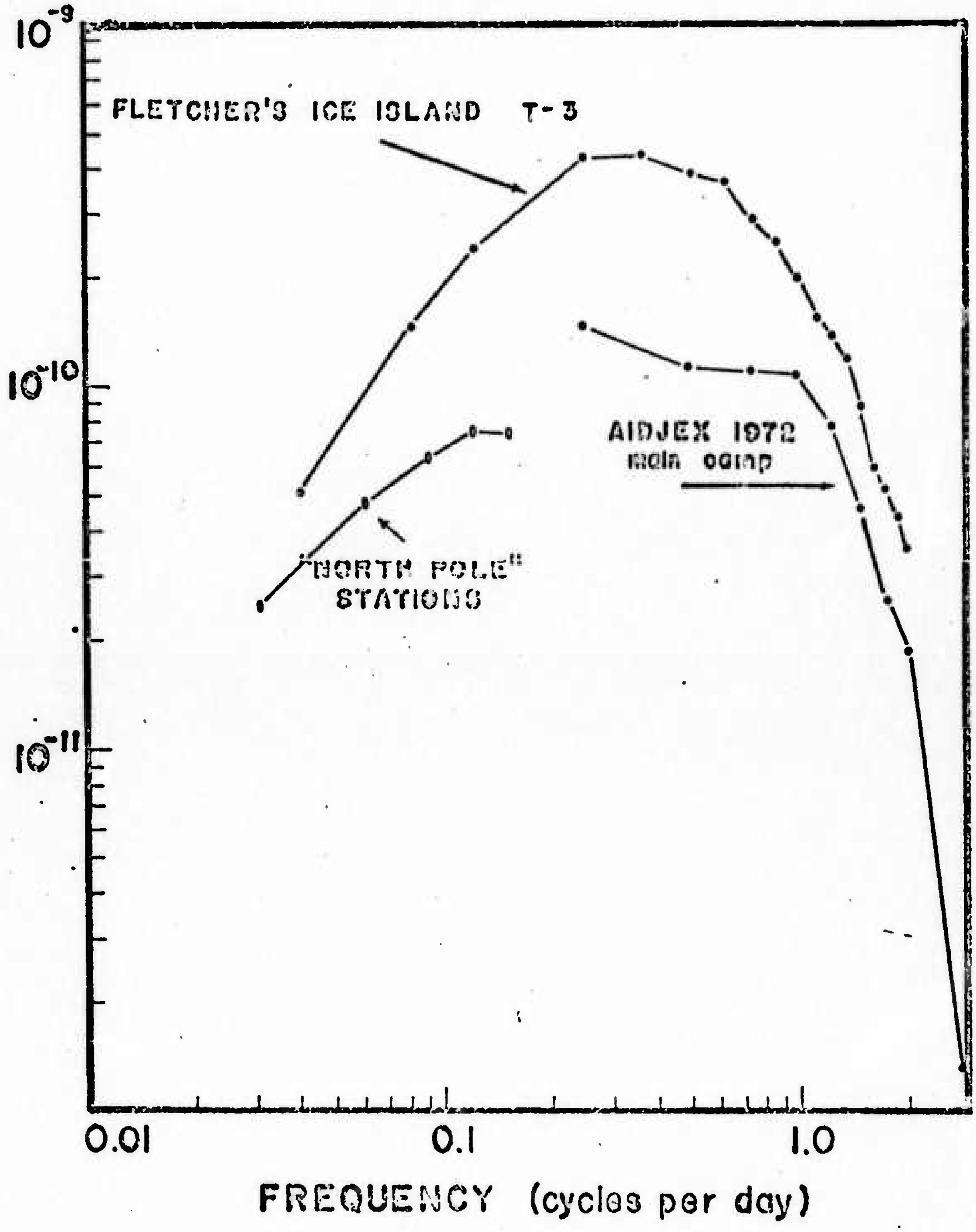
AIDJEX 1972
main camp
0.01
0.1
1.0
FREQUENCY (cycles per day)

Figure 4a

(4b)



10^{-9}
10^{-10}
10^{-11}
FLETCHER'S ICE ISLAND T-3
AIDJEX 1972
main camp
"NORTH POLE"
STATIONS
0.01
0.1
1.0
FREQUENCY (cycles per day)

Figure 4b

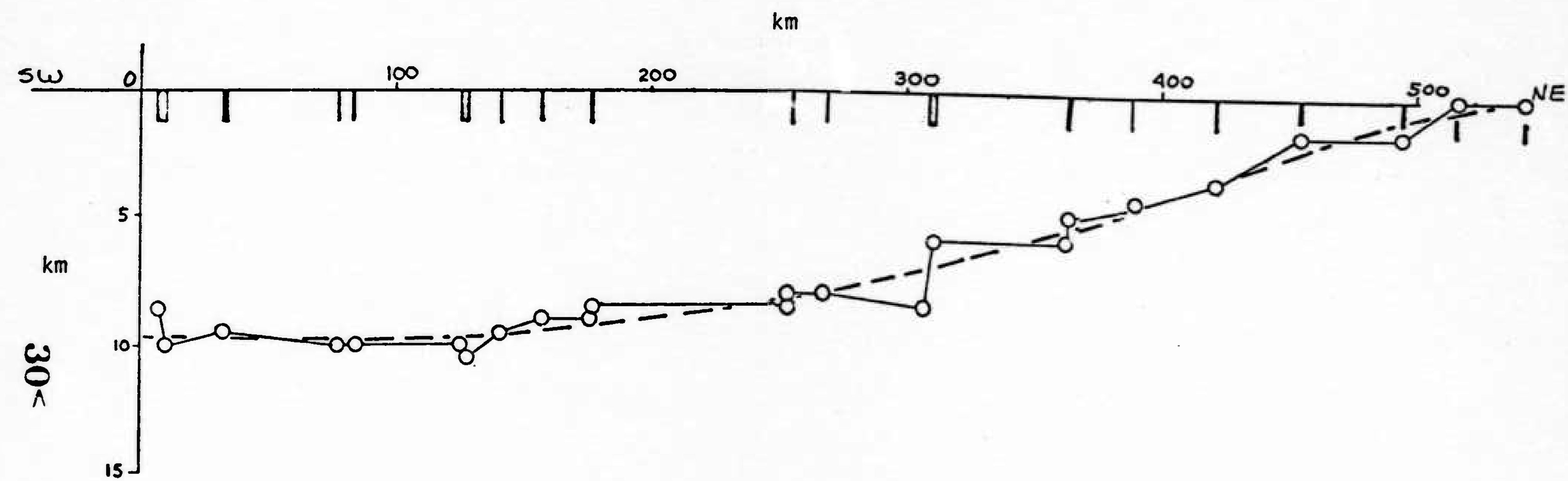


Figure 5

Air stress. An operational dynamic pack ice model requires that the field of wind stress be known. This involves both a theoretical and a practical problem.

The gradient wind at the top of the planetary boundary layer can be derived from maps of atmospheric surface pressure. The problem is to relate the surface stress to the gradient wind, taking into account the influences of roughness and stratification. This is one of the oldest, most fundamental, and most widely researched problems of geophysical fluid dynamics. All theoretical treatments of this problem are approximate, or require data of a degree of completeness and sophistication that cannot generally be achieved. In each particular case it is left to the skill of the investigator to choose those theoretical concepts that produce the best results for the particular set of circumstances. An extensive review of the entire problem was given in AIDJEX Bulletin No. 20 (May 1973). In an additional article (AIDJEX Bulletin No. 23, January 1974) the same author shows that a usable relationship exists between the geostrophic drag and the stratification of the boundary layer which, in turn, may be related to the angle of turning of the wind through the boundary layer. The observations planned for the Main Experiment will enable us to choose the model which is most consistent with the data.

The problem of acquiring accurate wind fields for the application to ice dynamics would be greatly alleviated if direct surface wind observations were available from the automatic data buoys. The frequent deposition of rime on all exposed surfaces on the one hand, and the lack of sufficiently large electrical power sources for de-riming, makes it at present impossible to use conventional anemometers. Although various efforts are under way to develop new all-weather wind sensors (including suitable devices for maintaining

a reference azimuth to compensate for buoy rotation) we do not expect that such sensors will be available for some time.

Water stress and general oceanography. A large amount of data has been gathered on the structure of the mixed layer beneath the pack ice. The scientific problems associated with the fluxes of momentum and heat in that layer are analogous to those encountered in the atmospheric boundary layer (with the exception of the salt flux). However, while the planetary boundary layer in the atmosphere has a thickness of the order of 10^3 m and can be observed only by means of tall masts, balloons, aircraft, or remote sensing methods, the planetary boundary layer in the oceans is only on the order of 10^1 m thick and is easily observed in its entirety.

Closely spaced observations of the horizontal current in the mixed layer, such as were obtained during the 1972 pilot study, can be used to evaluate the classic Ekman equation (in a form integrated with respect to the vertical coordinate) to obtain directly the stress exerted by the water on the ice. This method is extremely convenient as it considers only the change in time of the total horizontal momentum contained in the Ekman layer, and requires none of the complex theory needed in the atmospheric boundary layer.

The point has often been made that the pack ice provides a stable platform for observations of general interest in oceanography which are extremely difficult and costly in the open ocean. During the multi-station observations of AIDJEX it was found that baroclinic eddies exist at depths between 50 and 300 meters (see, for example, Bulletin No. 23, January 1974). These eddies have diameters of 10-20 km and are believed to develop at the

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boundary between water masses influenced by the Pacific regime and by the local arctic regime. Eddies of this kind have been found and studied in the central Atlantic Ocean (MODE). Dynamically they are analogous to the cyclonic eddies of the mid- and high-latitude troposphere, but their role in the large-scale oceanic mixing is not clearly understood.

Remote sensing. AIDJEX has profited from the remote sensing programs of NASA and NOAA. The discovery that the emissivities in the 19 and 37 GHz bands are significantly different for first-year and multiyear sea ice has opened up unprecedented possibilities of monitoring and studying the global sea ice balance (by satellite-borne microwave imagers) and the detailed composition of the pack ice in a specific region (by airborne observations). During the 1972 pilot study, a joint experiment was conducted by NASA, USGS, Environment Canada, and AIDJEX to provide ground truth for the remote sensing overflights of the NASA "Galileo" aircraft (AIDJEX Bulletin No. 18, February 1973).

The images from ERTS, in conjunction with aerial photographs, have given us, for the first time, a synoptic view of the large-scale morphological features of the pack ice. A new side-looking radar device and other remote sensing instruments were tested in spring 1974 in a series of flights across the shear zone north of Barrow in a joint project between USGS and CRREL.

The field of remote sensing technology is one in which it is especially difficult to separate the things that can be done from the things that should be done. The inaccessibility of the polar regions makes polar research an obvious prime user of remotely sensed data, but the published literature clearly indicates that efforts toward analyses and interpretations of these data must be increased so that the rapid progress of technology does not cause the method to overtake the purpose.

The most important information to be obtained for AIDJEX by remote sensing methods is the ice thickness distribution (see following section). No single and immediately applicable method exists to obtain this information. The plan for remote-sensing observations during the Main Experiment, which is presently being formulated, will provide for a combination of photography, infrared emission profiles and images, and possibly microwave and radar data which should collectively give us an occasional check (several times during the year) on the ice thickness distribution computed by the dynamic model.

In addition, it would be highly desirable to have a few sets of sequential photographic or ERTS-type images of the ice to determine the strain field in much greater spatial detail (but with less numerical precision) than will be possible using the position measurements at the manned stations.

We hope and expect that, in addition to the remote sensing data specifically required for the pack ice model, a wide range of additional data will be acquired that will serve sea ice research in general.

Modeling. In addition to management, operations, and technical coordination, an important activity of the AIDJEX Office is the development of the numerical model that will utilize the data acquired during the Main Experiment in 1975-76. This model in its present state has evolved from numerous studies in the past and in continuous exchange of ideas between the AIDJEX Modeling Group and others at USGS, CRREL, and other institutions.

On the basis of several theoretical studies in plate mechanics, mostly concerned with the mechanics of pressure ridge formation, it was decided that, from the wide range of possibilitites to attempt a description of pack ice as a geophysical material, one should be chosen that contains a number of

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mesoscale phenomena which add up to a composite constitutive relationship that realistically describes the large-scale behavior of the ice.

The work plan of the AIDJEX Modeling Group is presently concentrated on perfecting the ice model to a point where the field observations expected to begin in spring 1975 can be utilized with a minimum time delay. The field data will serve the purpose of both "driving" and checking the model. The structure of the ice model and its relation to global atmosphere and ocean models and to applications are shown in Figure 6.

The basic ingredients of the mathematical representation of the physical behavior of any medium are:

1. equations of motion;
2. a constitutive law for the material;
3. conservation of mass (including sinks or sources); and
4. the first law of thermodynamics.

Before AIDJEX, sea-ice models used clear and realistic formulations only for item 1. Item 2 is now tentatively formulated as an elastic-plastic law including a property similar to strain hardening. On a sub-grid scale, the material is assumed to be densely fractured by processes not considered in the model. Further, the strength of the material is determined by its statistical thickness distribution (including open water).

An important step forward was the identification of this thickness distribution as the key state variable of the pack ice. By means of a thermodynamic model of ice growth and decay, developed earlier, it was possible to establish not only a statement of the conservation of mass, but also to formalize the way in which the mechanical behavior and the thickness distribution (freezing and melting) affect each other.

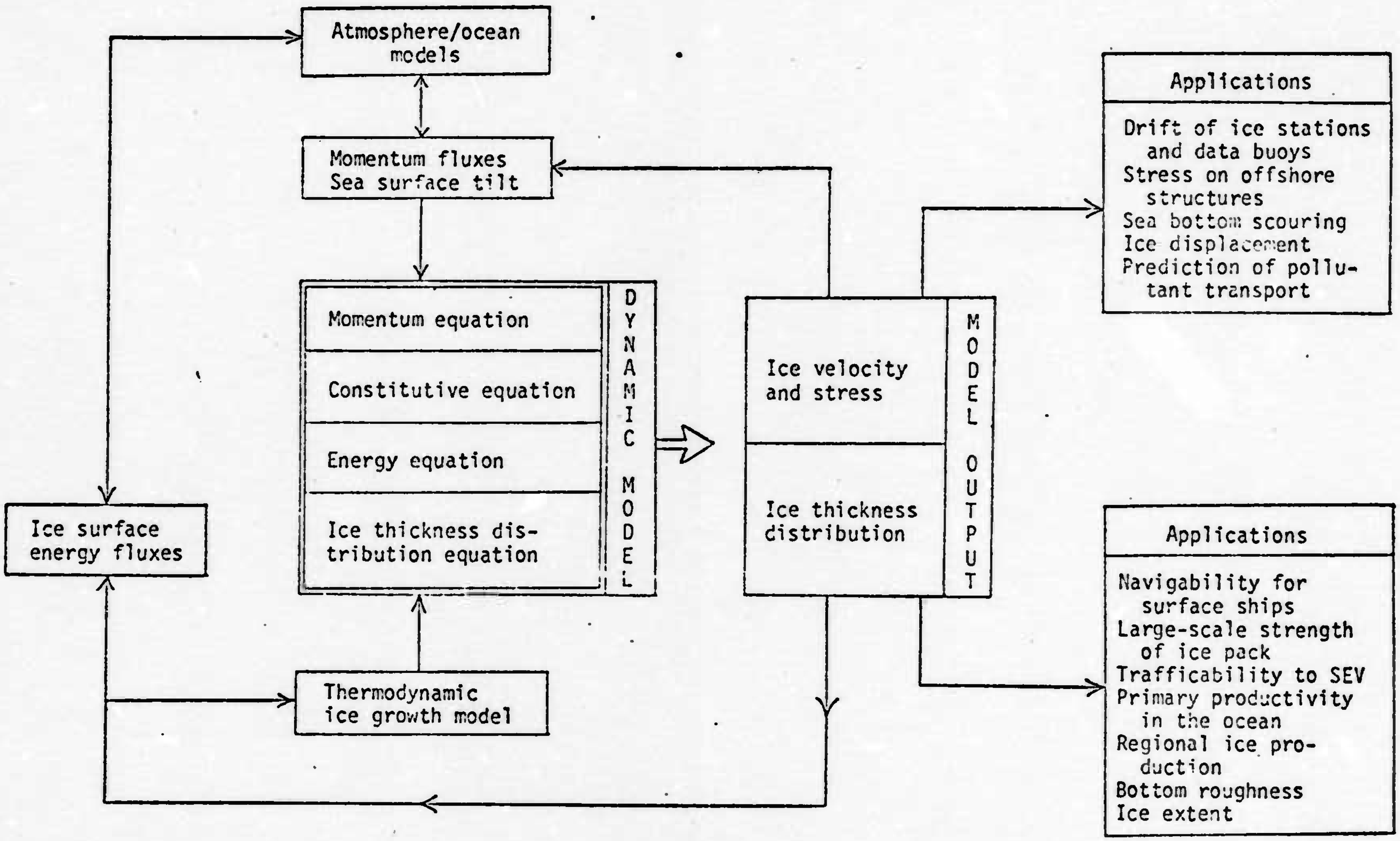
Atmosphere/ocean models
Momentum fluxes
Sea surface tilt
Momentum equation
Constitutive equation
Energy equation
Ice thickness distribution equation
DYNAMIC MODEL
Ice velocity and stress
Ice thickness distribution
MODEL OUTPUT
Applications
Drift of ice stations and data buoys
Stress on offshore structures
Sea bottom scouring
Ice displacement
Prediction of pollutant transport
Applications
Navigability for surface ships
Large-scale strength of ice pack
Trafficability to SEV
Primary productivity in the ocean
Regional ice production
Bottom roughness
Ice extent
Ice surface energy fluxes
Thermodynamic ice growth model

Figure 6

The fourth requirement, to satisfy the first law of thermodynamics, is difficult to meet. Work done on the ice by deformation is dissipated into surface energy by fracturing, floe-to-floe friction, and the potential energy stored in pressure ridges. There is reason to believe that the last part is the largest. The present model assumes that the entire strain work goes into ridge building.

A detailed progress report, setting forth the theoretical foundation of the model and presenting the results of preliminary calculations, was published in May 1974 as AIDJEX Bulletin No. 24.

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LEAD EXPERIMENT

In the AIDJEX Scientific Plan of 1972 it was proposed to repeat a type of experiment first conducted in 1961 and aimed at elucidating the role of open leads in the total heat balance of the Arctic Ocean. During most of the year, extremely large temperature differences exist between the surface of thick ice and the surface of openings (leads or polynyas) produced by the deformation of the ice. This variable area of open water may, during some parts of the year, be the controlling parameter in the overall heat and ice balance.

The AIDJEX Lead Experiment was successfully conducted between 25 February and 11 April 1974. With logistics support from the Naval Arctic Research Laboratory at Barrow, Alaska, a joint research group from Oregon State University and the University of Washington acquired a set of excellent data on the modification of both the atmospheric and the oceanic boundary layer in the vicinity of an open lead. Fully instrumented wanigans were deployed by helicopter to suitable locations reconnoitered by NARL aircraft at distances between 20 and 40 kilometers north-northeast of Barrow. A total of five sites were occupied for periods between one and three days. One site had to be abandoned prematurely because of rapid closure of the lead. In addition, observations of the atmospheric boundary layer were obtained over two artificial ponds created by pumping water on top of the ice on Elson Lagoon near NARL.

The rapidly shifting ice in the vicinity of Barrow and the rapid freezing of water during the arctic spring, as well as the sophistication of the instruments used in the experiment, required painstaking preparations, high-precision logistics, and a considerable amount of luck. The latter still seems to be with us.

Once again, the Naval Arctic Research Laboratory and its staff proved to be a vital source of operational support. Detailed accounts of the Lead Experiment by the principal participants appear in AIDJEX Bulletin No. 25, June 1974.

AIDJEX ORGANIZATIONAL STRUCTURE AND PARTICIPANTS

AIDJEX is structured as shown in Figure 7. A Joint Panel on AIDJEX (now transformed into the Joint Panel on POLEX, with AIDJEX as a secondary task) was established by the National Academy of Sciences at the request of the National Science Foundation. This Panel advises both the federal funding agencies and the AIDJEX Coordinator, and evaluates and adjudicates in scientific matters. The AIDJEX Committee, composed of participating scientists and agency representatives, advises the AIDJEX Coordinator in both scientific and operational matters, and reviews research proposals, primarily with respect to their relevance to the objectives of AIDJEX.

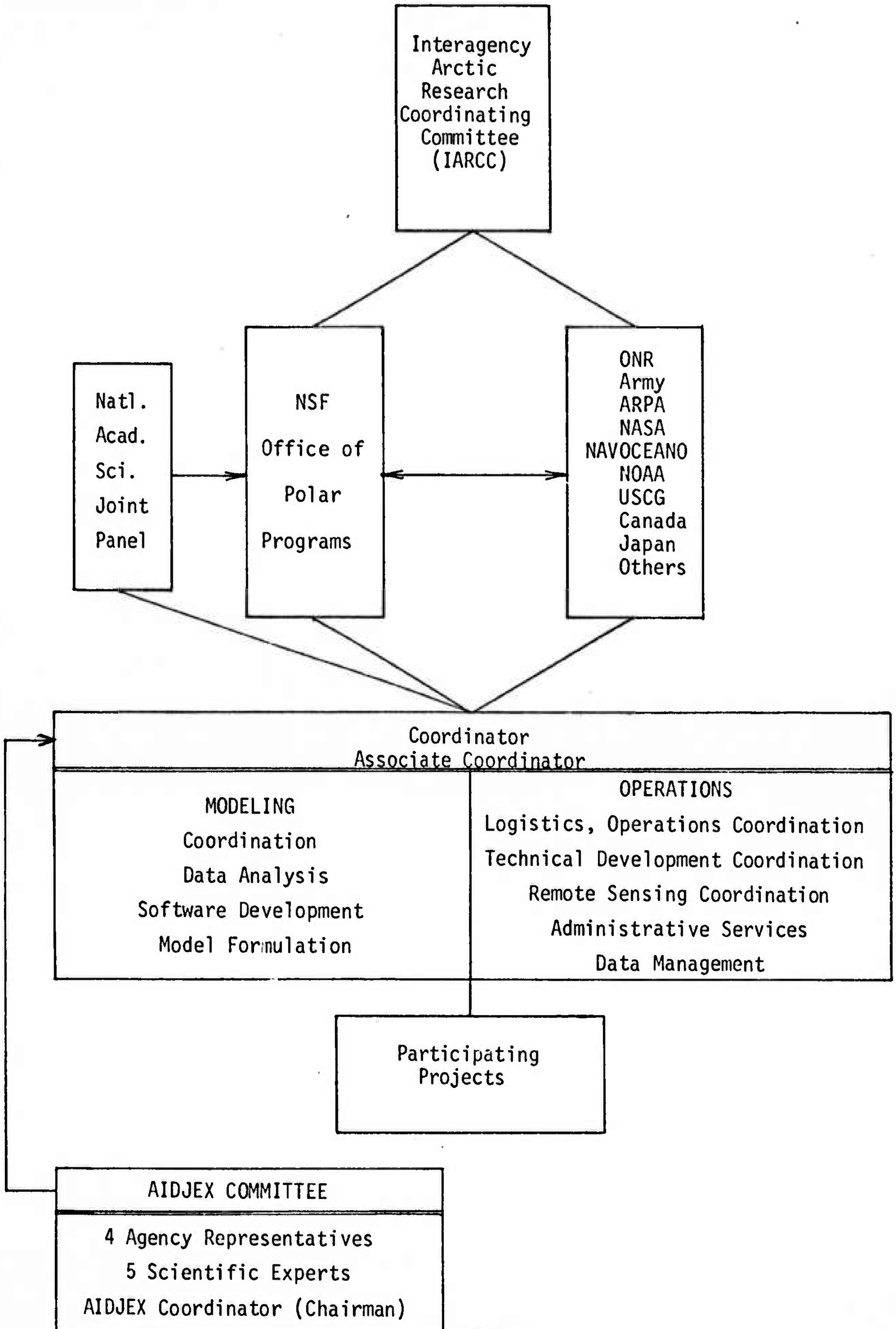
The staff of the AIDJEX Office at the University of Washington is grouped into three functional categories: 1) the management staff (with the Coordinator being both a project director on behalf of NSF and an employee of the University); 2) a technical staff responsible for logistics, hardware such as the data acquisition system and the buoys, and the data bank; and 3) a scientific staff responsible for the comprehensive model that is expected to be the main result of AIDJEX, and for developing concepts of theory and procedures as required for the experiment.

The J(oint) in AIDJEX represents the participating projects as shown in Figure 7. Their number reached a peak of 26 in the 1972 pilot study (see

AIDJEX Bulletin No. 14, July 1972). It was not only the budget cuts that have occurred in the meantime but also an intentional concentration on the scientific focus of AIDJEX that has reduced the number of participants since then. Major participants in the 1975-76 Main Experiment will be the Lamont-Doherty Geological Observatory of Columbia University, the U. S. Army Cold Regions Research and Engineering Laboratory, the U. S. Geological Survey in conjunction with NASA, and the National Data Buoy Office of NOAA, the University of Alaska, and several Canadian participants supported through the Polar Continental Shelf Project.

Establishing the AIDJEX Office and Modeling Group at a large university with strong programs in earth sciences and engineering has proven highly beneficial. The University's faculty has been a convenient source of scientific talent which either can be applied directly to the various program elements or is available for both formal and informal consultation as problems arise. Further, graduate students provide a pool of trained personnel, and usually between six and ten have been working part-time on the program while furthering their own training. It is well known that legislators, regents, and administrators who control state universities with a primary responsibility in undergraduate education, are sometimes not entirely sympathetic to highly mission-oriented research projects. On the other hand it is, with a few exceptions, those large state universities that have the diversified intellectual resources to tackle complex and multidisciplinary research tasks. We believe that, with the assistance (and sometimes forbearance) of administrators both in the federal agencies and in the university, AIDJEX will provide further experience in finding optimal compromise arrangements in the operation of such projects.

The initial scientific plan for AIDJEX, first formulated in 1969, was the outgrowth of a variety of research projects supported since IGY 1957-58 by the Office of Naval Research (notably its Arctic Program). It was enthusiastically


Interagency Arctic Research Coordinating Committee (IARCC)
Natl. Acad. Sci. Joint Panel
NSF Office of Polar Programs
ONR
Army
ARPA
NASA
NAVOCEANO
NOAA
USCG
Canada
Japan
Others
Coordinator
Associate Coordinator
MODELING
Coordination
Data Analysis
Software Development
Model Formulation
OPERATIONS
Logistics, Operations Coordination
Technical Development Coordination
Remote Sensing Coordination
Administrative Services
Data Management
Participating Projects
AIDJEX COMMITTEE
4 Agency Representatives
5 Scientific Experts
AIDJEX Coordinator (Chairman)

received by the community of polar scientists informally convened in November 1969. Experienced science administrators have observed that research work in snow and ice and in the polar regions attracts a type of scientist who is typically competent, though rarely brilliant, enterprising, resourceful, hardy, and easy to get along with. Several examples could be given to show that both national and international panels or committees engaged in snow and ice research are generally among the most productive and least quarrelsome. From its inception, it was the virtually unanimous consensus of this community of scientists, that AIDJEX (roughly defined as it was at the time) was the only way in which a quantum jump in our understanding of sea-air interaction in ice-covered seas can be achieved.

AIDJEX Bulletin

In view of the cooperative nature of our project and its diversified participation and support, we considered it of the utmost importance that all activities must be documented and communicated to the community as rapidly as possible. The AIDJEX Bulletin, initiated in September 1970, attempts to strike a balance between quality and speed. It contains original scientific papers (often pre-publications of regular journal articles), status and progress reports on specific activities, plans and narratives of field exercises, performance evaluations of hardware, reports on conferences and working sessions, raw data of immediate use to investigators, translations of interest, and an occasional joke. By June 1974, 25 Bulletins with a total of about 3,000 pages were published. 700 copies are made of current editions.

Data Bank

In November 1971 a data bank was established which is managed by a full-time member of the AIDJEX Office staff and uses the University of Washington

Computer Center and the computer terminal located in the AIDJEX Office for data handling and retrieval. Inventories and acquisitions of the data bank are periodically reported in the Bulletin. The AIDJEX Office has, with the concurrence of the AIDJEX Committee, the NAS Joint Panel for AIDJEX, and the federal funding agencies, issued a statement which explicitly describes the basic obligations of the participating principal investigators and the working policies of the data bank. To date, the operation of the data bank and its dealings with individual investigators and other national data depositories have been highly satisfactory.

Financial Support and Budget Summary

As mentioned earlier, much of the research leading up to AIDJEX was supported by the Office of Naval Research. In 1970, when the National Science Foundation was designated "Lead Agency for the Extension of Arctic Research," it awarded the first substantial contract to the University of Washington for the establishment of the AIDJEX Office in the Division of Marine Resources. Since then, the support from both agencies, and particularly that from NSF, has increased substantially. While the support from NSF is split nearly evenly between science and operations, a large part of the ONR support has been in the form of operational and logistic support through the Naval Arctic Research Laboratory, which has been a vital element of our logistics. NOAA, through its National Data Buoy Office, is supporting the development of a buoy especially designed for various applications in ice-covered waters.

The NASA contribution primarily has been in the form of remote-sensing aircraft overflights during field experiments; coordination of the NASA flights with the AIDJEX program has been supported by USGS which has also supported modeling work. ARPA's support, originally for field experiments, is now directed toward the modeling effort.

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Canadian participation has primarily been through PCSP, including both scientific investigations and logistics support.

Table 1 summarizes funding support for the AIDJEX program through FY 1973 and shows the projected funding estimates through completion of the field program in FY 1976. The table also shows the rather favorable ratio between scientific programs and logistic support despite working in a remote and difficult environment.

ACKNOWLEDGMENTS

It should be evident from the preceding pages that AIDJEX has been a group effort in every respect. The participants have enjoyed the benefits and paid the costs which result from such an effort. The number of dedicated scientists and administrators who have advanced the project this far is so large, and their individual contributions are so varied, that they can be neither weighed nor enumerated at this time. The critical period for AIDJEX lies just ahead. The task of maintaining a sound and legitimate scientific focus while accommodating the individual motivation and competence of the participating scientists (all within tight budgetary constraints) will require the continuing support and goodwill we have enjoyed to date.

Inquiries and requests for reprints, Bulletins, or specific references should be addressed to AIDJEX Office, Division of Marine Resources, University of Washington, 4059 Roosevelt Way N.E., Seattle, Washington, 98105; telephone (206) 543-6613.

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AIDJEX FUNDING

(IN THOUSANDS OF DOLLARS)

	FY-70	FY-71	FY-72	FY-73	FY-74*	FY-75*	FY-76*
NSF	100	690	1,511	1,090			
ONR	120	332	720	486			
NOAA		60	99	15			
NASA		145	410				
NAVOCEANO		90	75				
ARPA		200	102				
MARAD							
USGS	2	15	20	40			
USCG		33					
CANADA	76	90	254				
JAPAN			50				
TOTAL	298	1,655	3,241	1,631	2,919	4,371	3,064
SCIENCE	106	1,060	2,174	1,160	2,481	2,550	1,697
LOGISTICS/ OPERATIONS	192	595	1,067	471	438	1,821	1,367

*Proposed expenditure levels

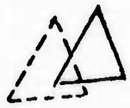
Table 1

CAPTIONS FOR FIGURES AND TABLE

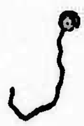
Figure 1

⊙ Approximate starting location of the manned stations of the "most austere" AIDJEX 1975-76

○ Approximate starting locations of the automatic data buoys AIDJEX 1975-76



Initial and final location of the triangle of manned stations of the 1972 Pilot Study.



Starting location and drift of data buoys deployed in conjunction with the 1972 Pilot study:

Buoy No. 1, operating	4/72	-	7/72	: 76 days
2	4/72	-	4/73	: 355 days
3	4/72	-	2/74	: 667 days
4	4/72	-	6/72	: 84 days
5	4/72	-	12/73	: 603 days
6	4/72	-	6/73	: 417 days
8	10/72	-	3/74	: 553 days

+ Originally proposed array of data buoys (now proposed as part of the U.S. contribution to POLEX)

Figure 2 The IRLS buoy in the foreground was recovered on 6 March, 1974 with the support of the Canadian Polar Continental Shelf Project. This buoy was the only one remaining in operation from a total of seven buoys deployed in 1972. The average life of these buoys was 1.1 years. The electronics of this buoy are enclosed in the pipe which reaches through the ice into the isothermal environment of the sea water.

Figure 3 Total area of station triangle determined by Navy Navigation Satellite System, 14 March to 25 April 1972. The net ice divergence during the 40 days of observations was 5.5%.

Captions (cont.)

Figure 4a Power spectra of the ice velocity determined from the drift of several Soviet "NP" stations, ice island T-3, and the AIDJEX 1972 stations.

Figure 4b Power spectra of ice acceleration derived from the same data. In both cases, there is no evidence of high-frequency motions with an appreciable amplitude.

Figure 5 Derived from ERTS I images: deformation of a straight line drawn on the pack ice of the Beaufort Sea, during a two-day period in March 1973.

|□ original location of ice features

○ location of the same ice features two days later

Figure 6 Structure of the AIDJEX dynamic ice model and its relationship to the global models of the atmosphere and the ocean. Also indicated are the nature of the expected model output and its potential applications to practical problems.

Figure 7 Organizational structure of AIDJEX.

Table 1 Funding of AIDJEX. Figures shown for FY 1970 through FY 1973 represent actual expenditures. Figures for FY 1974 through FY 1976 are estimates and only totals are shown. Their actual breakdown will not be available until accounts are completed which, depending on contractual arrangements, in some cases do not coincide with the federal fiscal cycle.